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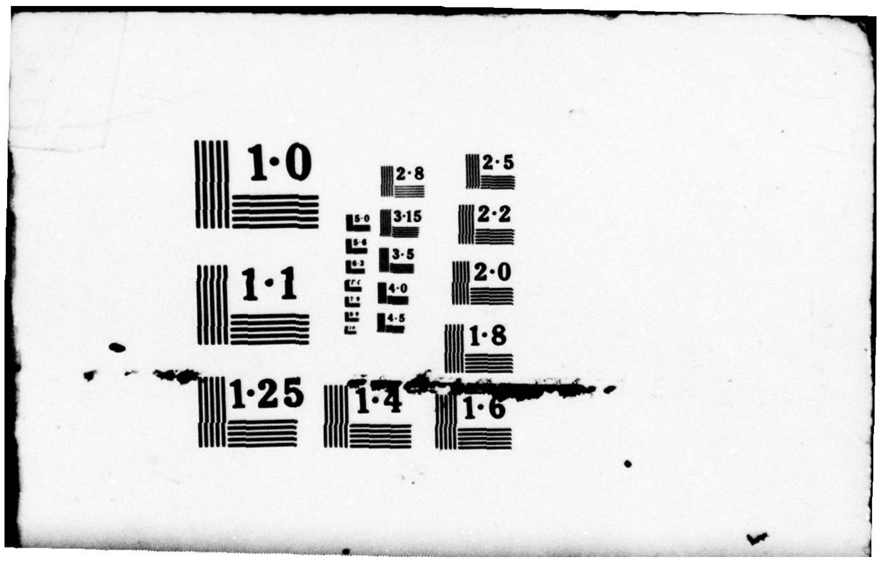
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NRL Memorandum Report 3919

Feasibility Study of Ferrite Use at MM Waves

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Electronics Technology Division

January 26, 1979

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A survey was conducted in order to establish the usefulness of ferrites at millimeter wave frequencies. We expect hexagonal ferrites to be operational up to 500 GHz for non-reciprocal device applications. The limiting factor of these type of ferrites at millimeter wave frequencies may possibly be that the dielectric propagation loss is too high. Beyond 500 GHz antiferromagnetic materials may have to be explored for possible uses.

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CONTENTS

FEASIBILITY STUDY OF FERRITE USE AT MILLIMETER WAVES

Although the interest cycle of millimeter (mm) waves is 10-12 years, it appears from recent surveys[1] that there are presently real system needs[1] within DOD at mm waves. All indications are that this technology will take hold this cycle. The system needs are well recognized and catalogued[1] and we will not dwell upon them. In this report we address ourselves as to what role ferrites can play at mm waves.

This report is subdivided into four sections. The first section deals with general background on mm waves and ferrites. The second section concerns itself with projected performance of ferrite devices at mm waves. The third section discusses the technical limitations of ferrites at mm waves and the final section summarizes all the conclusions concerning ferrite uses at mm waves.

I. General Background

Before we discuss the general properties of mm waves and ferrites we define the mm wave region as that region which covers frequencies from ~ 40 (7.5mm) to ~ 1000 GHz (0.3 mm). It is obvious that mm waves run into "stiff"

Note: Manuscript submitted December 1, 1978.

competition from the microwave (below < 40 GHz) and optical (> 1000 GHz) frequencies for radar, satellite, radiometry and microwave communication applications. Thus, in order to "compete" with the other two technologies, whatever application is considered must be unique to mm waves. Listed below are some important properties of mm waves.

A. Important Characteristics of mm Waves

(1) Broad Bandwidths

Since mm waves operate at high frequencies in comparison to X-band, for example, there is a large frequency region available for transmitting information over a wide frequency band. Only optical frequencies have larger bandwidths.

(2) Narrow Beamwidth

Since by necessity waveguide dimensions at mm waves are small compared to those at X-band, the beamwidth must also be small. For example, at 95 GHz a typical beamwidth for radar applications is ~ 0.2 degrees. At X-band the beamwidths are typically a factor of 10 larger.

(3) Small System Size and Weight

(4) Propagation[3] through Electron Plasma

One method of communicating with a reentering spacecraft surrounded by an electron plasma is by mm waves.

(5) Propagation above sea water.

The low-lying evaporation duct over water can trap electromagnetic radiation and result in considerably longer ranges when both antenna and target are at low elevations. This propagation in the "duct" is said to be better at higher frequencies[4].

(6) Atmospheric Attenuation

Millimeter waves are readily absorbed in the atmosphere. It is well known that at 95 GHz there is an atmospheric absorption minimum (0.69 db/Km). However, the atmospheric attenuation at 95 GHz is still high compared to X-band attenuation (0.008 db/Km). At 60 GHz the attenuation is 30 db/Km. The attenuation increases at all frequencies as the water vapor content increases in the atmosphere. It is possible to transmit and receive[5] a 95 GHz signal at ranges of ~ 10 miles with a 10 watts source. This is a very limited range in comparison to X-band. However, at 95 GHz the total absorption loss for signals passing through the entire atmosphere at near-zenith angles is only[3] one db.

B. Ferrite properties at mm waves

(1) Permeability tensor

The microwave properties of the ferrites are described by the permeability tensor which relates the

microwave induction $\vec{b}$ to the microwave magnetic field intensity $\vec{h}$. For a single-domain (or magnetically saturated) ferrite magnetized in the z-direction the tensor is

$$\overleftrightarrow{\mu} = \begin{vmatrix} \mu_{xx} & \mu_{xy} & 0 \\ \mu_{yx} & \mu_{yy} & 0 \\ 0 & 0 & 1 \end{vmatrix} \tag{1}$$

where

$$\mu_{xx} = 1 + \chi_{xx}$$

$$\mu_{xy} = -j\,\chi_{xy} = -\,\mu_{yx}$$

$$\mu_{yy} = 1 + \chi_{yy}$$

χ_{ij} is the susceptibility tensor element where

$i, j = x, y$.

$$\chi_{xx} = \frac{4\pi M \left[(H + j\frac{\Delta H}{2}) + N_y M \right]}{\Delta}$$

$$\chi_{xy} = \frac{4\pi M\, \omega/\gamma}{\Delta}$$

$$\chi_{yx} = -\,\chi_{xy}$$

$$\chi_{yy} = \frac{4\pi M \left[(H + j\frac{\Delta H}{2}) + N_x M \right]}{\Delta}$$

$$\Delta = H_r^2 - (\omega/\gamma)^2 + j\,\Delta H \left[H + \frac{(N_x - N_y)M}{2} \right]$$

$$H = H_{applied} - N_z M + \frac{2|K|}{M}$$

$$H_r^2 = (H + N_x M) \cdot (H + N_y M)$$

ΔH = FMR Linewidth at half power.

H_r = FMR field

$H_{applied}$ = External applied field

N_α = demagnetizing factors

α = x, y and z

In the above formulation of the permeability tensor the easy axis of magnetization is assumed to be along the z-direction. It should be pointed out that <u>only</u> in a biasing field condition is the permeability a tensor quantity.

2. Classes of Microwave Ferrite Devices

There are essentially two classes of microwave ferrite devices: Microwave devices for which the ferrite is tuned to ferromagnetic or ferrimagnetic resonance (FMR) and devices which are magnetically tuned away from FMR. Devices tuned at FMR are magnetically active at FMR and usually one attempts to maximize the imaginary part of the permeability. Depending on the shape of the sample, it requires ~ 3000 Oe to tune a cubic ferrite material to FMR at X-band ($f = \gamma H$). Typically $\gamma \simeq 2.8$ MHz/Oe. At mm waves cubic ferrites require impractical large

fields for resonance, e.g. at 95 GHz fields of $\sim$ 35 KOe are required. Devices that are tuned away from FMR make use of the Faraday rotation properties of the ferrite. For non-reciprocal device applications the off diagonal element of the permeability tensor is a quantitative measure of the rotation effectiveness. At X-band it is only required to bias the cubic ferrite to a single domain configuration which can be done in small fields (300-500 Oe). However, at these fields the ferrite would be magnetically inefficient at mm waves, since it would be tuned significantly away from FMR. With hexagonal ferrites fields of 300-500 Oe are sufficient to produce a single domain configuration and are more efficient than cubic ferrites, since hexagonal ferrites are biased relatively nearer to FMR because of the high uniaxial anisotropy field.

We would like to put to rest an often invoked but impractical notion that to improve mm wave performance of most ferrite devices, which are currently tuned to frequencies away from FMR, it is only required to increase $4\pi M$ (the magnetization) of a typical cubic ferrite. This statement or these type of statements are impractical for two reasons: (a) As far as we know there are presently no spinel, garnet or cubic ferrite insulating materials which have a value of $4\pi M \gtrsim 6$ KG and even given this

large $4\pi M$, b) at mm waves these ferrites become inefficient. As such, high dc magnetic fields (> 30 KG) are needed in order to make cubic ferrites active at mm waves.

3. Hexagonal Ferrites

Beljers[7] pointed out in 1954 that the large internal magnetic uniaxial anisotropy field in M-type ferrites causes FMR to occur in the millimeter-wavelength range. The chemical formula of a M-type ferrite is

$$M\, I_x\, J_x\, Fe_{12-2x}\, O_{19}$$

where M ≡ Ba, Sr, La, Pb, Ca; I and J are impurities and their valences add up to +6. Typically I ≡ Co, Ni, Zn and J ≡ Ti; I = J = Al and Ga. The main characteristic of the M, W, Y and Z-type ferrites[2] is their high uniaxial magnetic anisotropy field. This "internal" magnetic field allows the ferrite to be magnetically active ≥ 500 GHz.

Presently, there is some microwave data on the hexagonal ferrites but not enough to begin to deduce useful information. We are considering the M-type hexagonal ferrites for mm wave use on the basis that (a) there is some microwave data[8] and (b) they are the most characterized[2] ferrites within the hexagonal class.

4. Quantitative Examples

For practical ferrite devices one usually requires

(1) $\Delta H \ll H_r$

(2) $H_{applied}$ small (300-500 Oe)

For simplicity let us assume the following condition

(3) A thin rod with H || z-direction and || to the rod axis ($N_z = 0$; $N_x = N_y = 2\pi$).

It is understood that $H_{applied}$ is of sufficient magnitude as to saturate the sample into a single domain. For a <u>reciprocal</u> phase shifter the important quantity is χ_{xx}, since the phase shift between the + and -z wave propagations is proportional[9] to χ_{xx}. We will calculate the susceptibility tensor elements χ for a typical cubic ferrite with operating frequencies of 9 GHz and 100 GHz and repeat the same numerical calculations for a hexagonal ferrite whose uniaxial anisotropy field $H_A = \frac{2|K|}{M} \sim 25$ kOe. H_A serves the same purpose as a biasing external magnetic field in this case. For both types of ferrites we use $4\pi M = 4000$ G and $g = 2$. The results of the calculation are tabulated below. The quantities in parantheses refer to the hexagonal ferrite.

Frequency (GHz)	χ_{xx}	μ_{xx}
9	-0.735 (0.148)	0.265 (1.148)
100	-0.006 (-0.265)	0.994 (0.735)

At 9 GHz we note that the susceptibility of the "cubic" ferrite is greater than the hexagonal ferrite susceptibility. The opposite is true at 100 Ghz.

A word of caution is in order here. The high values of H_A are usually obtained at the "expense" of low values of $4\pi M$, since $H_A = \frac{2|K|}{M}$. There can be a number of ferrite materials which intrinsically can provide high values of H_A, but there are few that can provide both high H_A and $4\pi M$ values. Although high values of H_A relax the demand for high values of $4\pi M$, it would still be practically useful to obtain hexagonal ferrite materials operating at mm waves with a nominal value of $4\pi M = 5000$ G. Furthermore, there are even fewer hexagonal ferrites which have $4\pi M \geq 5000$ G and narrow FMR linewidth ($\Delta H < 50$ Oe). Thus, the criteria for a practical uniaxial ferrite at mm waves is that it should have high values of K and M such that the ratio is also high. Besides the above criteria the ferrite should exhibit a narrow linewidth. I believe that an uniaxial ferrite material exhibiting the following properties

$$H_A \geqq 50 \text{ kOe}$$

$$4\pi M = 5000 \text{ G}$$

$$\Delta H \geq 50 \text{ Oe}$$

is not an unrealistic goal. We will refer to the above parameters later in the text as "idealized" parameters.

Let us now project mm wave device performances <u>not</u> on the basis of an idealized ferrite but on the basis of whatever limited data are available in the literature.[2,8]

II. PROJECTED UNIAXIAL FERRITE DEVICE PERFORMANCES

We will assume in these projections a frequency of 95 GHz and also assume parameters appropriate to selected hexagonal ferrites.[2,8]

A. Ferrite Filter

Presently, there are no tunable magnetic field filters at mm waves. It is possible to fabricate tunable FMR filters using hexagonal ferrites. The Q of the resonant filter would be roughly

$$Q \sim \frac{H_A}{\Delta H} \sim 500 - 1000, \text{ at very high values of } H_A.$$

B. Ferrite Isolator

There are essentially three types of ferrite isolators: resonance isolator, field displacement isolator and Faraday rotator isolator.

1. For a resonance isolator one makes use of FMR. Since it would require magnetic fields up to 40 kOe to operate near 100 GHz with cubic ferrites, hexagonal ferrites, with their internal bias field, H_A, are ideally suited for this device application. It has been demonstrated[10] in a laboratory device that with small

biasing fields (~ 500 Oe) the M-type hexagonal ferrites can provide 20 db isolation at 95 GHz. One advantage of using resonance isolators is that the ferrite material can be placed on the metal waveguide and, therefore, they can be used at high power levels (~ 100 Watts, cw). In a waveguide device configuration it is estimated that thin (~ 20 μm) slabs of hexagonal ferrite at 95 GHz are sufficient[11] to realize the full capabilities of a resonance isolator. Presently, there are no commercial resonance isolators at mm waves. Power isolators are very important in developing practical high power generators at mm waves.

2. The field displacement isolator makes use of the phenomenon that the rf electric field distribution inside a waveguide and next to a ferrite is different for the + and -z-direction of propagations of the em wave. Hitachi[12] makes such an isolator using a cubic material with an isolation of 20db at mm waves. Isolation of 50 db at 60 GHz have been realized[13] using barium ferrite which is a hexagonal ferrite.

The dielectric loss of barium ferrite provided[13] sufficient attenuation so that it was not necessary to use a resistive film in conjunction with the ferrite. It is suspected that for this particular case[13] sample

impurities of Fe^{2+} in barium ferrite provided the loss mechanism. It should be pointed out that this type of isolator is inherently a low power isolator.

3. There are presently many commercial Faraday rotator isolators available. Cubic ferrites are often used in commercial type isolators at mm waves. There is no special advantage in using hexagonal ferrites except less material is required for Faraday isolators.

C. Phase Shifters

One of the important application of phase shifters is for electronically scanned phased array antennas. For this application at mm waves one would like a phase shift of ~ 500° and less than 2 dB attenuation for a given device element.[14] There are no commercial phase shifter devices which can satisfy the above requirement. Besides the phase shift and attenuation requirements, the problem of tolerances must be solved at mm waves. As the wave-guide dimensions become smaller and smaller with increasing frequency, fabrication processes become more tedious and difficult and, of course, expensive. There are two[15,16] novel schemes which make fabrication of phase shifters simpler: (a) arc plasma spraying[15] and (b) the dual mode phaser technique[16]. Presently, lithium ferrite appears to be a popular material even at

95 GHz. An attempt should be made to use hexagonal ferrite materials in these two fabrication techniques.

D. Circulator

Commercial circulators are rated at 16-20 db isolation with 1-2.5 db insertion loss. Cubic ferrite materials are used principally in commercial types. 50 to 100% improvement in the isolation with the same insertion loss has been obtained from turnstile[17] and planar circulators.[18] The turnstile[17] circulators are narrow band (1-2 GHz). Planar circulators[18] also exhibit high isolation (~ 25 db) and low insertion loss using garnet materials, but they were operated only at 15 GHz.[18] It is projected that planar circulators can be made to operate at mm waves with the same characteristics[18] as above. The planar configuration allows simpler and cheaper fabrication. The liquid epitaxy technique would be ideally suited for "growing" thin layers (10 μm) required for these devices. Isolation of 35 db and bandwidths of 1.5 GHz were obtained at 70 GHz using cubic ferrites in the turnstile[17] design. However, it is not clear that hexagonal ferrites can improve the bandwidth beyond 1.5 GHz at mm waves in this design.[17]

E. Frequency Doubler

Due to increased atmospheric absorption, there is

a high priority for high power sources at mm waves. As a rule the amount of practical[19] power generated by a source falls off rapidly with increasing frequency. Frequency doubler devices can be useful for extending high power capability to mm wave frequencies.

Presently, there are no commercially available frequency doublers efficient at mm waves. Research into ferrite frequency doublers ceased about 20 years ago. However, it is significant that a conversion efficiency of -3.5 db was obtained[20] with input power of 32 KW using cubic ferrites. Since cubic ferrites were used, the device was necessarily near X-band. These results are important because the conversion was realized at power levels well above the level possible with the usual silicon crystal multiplier and because of their[20] surprisingly high efficiency. Since the ferrite frequency doubler makes use of nonlinear FMR, hexagonal ferrites in a planar configuration would be ideally suited at mm waves. The conversion efficiency in such a device is proportional to $4\pi M/\Delta H$. Obviously, for this application there is high premium for high values of $4\pi M$ (~ 5-6000 G) and low linewidths (~ 50 Oe) hexagonal ferrites.

F. Power Limiters

It is well known that sensitive detectors is one

of the top priority in an engineer guide to design mm wave systems. However, sensitive detectors readily burn out as local electric fields become extremely high at mm waves. It is obvious that some sort of power limiters are needed in conjunction with sensitive detectors. Presently, there exists a commercial electronic feedback control limiter which involves both active and passive elements. A ferrite limiter uses only one passive element - the ferrite material.

The basic physical principal[22] of the ferrite limiter involves the onset of nonlinear behavior of the rf magnetization at the critical magnetic driving field intensity, h_c. At this point, the transfer of energy from the uniform precession of the spin dipoles to spinwaves and, hence, to the lattice in the form of heat provides several means for limiting the level of the rf power transmitted in a microwave component containing a ferrite.

Of the two Suhl[22] processes allowed for transferring energy from the FMR uniform mode to spinwaves only one process is energetically possible at mm waves. The critical field for which saturation occurs is

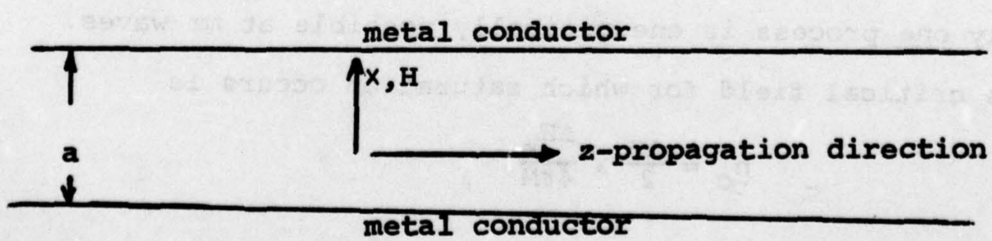
$$h_c = \frac{\Delta H}{2} \times \frac{\Delta H_k}{4\pi M}$$

where ΔH_k = Spinwave linewidth. Hexagonal ferrites should provide H_A, $4\pi M$, ΔH and ΔH_k required to produce practical power limiters at mm waves. Using ideal values of $\Delta H = \Delta H_k = 50$ Oe and $4\pi M = 5000$ G we obtain $h_c = \frac{1}{4}$ Oe which is reasonably small.

Finally, although we have not discussed other microwave ferrite devices, such as: ferromagnetic amplifiers, delay line, ferrite modulators etc., we feel that the ones we have discussed form the nucleus of microwave devices that need special attention, if this technology is to expand and take hold.

III. High frequency limitations of ferrites

Assuming that one is successful in preparing idealized hexagonal ferrites for mm wave use, the limiting factor which would prohibit their use is the propagation loss. In this section conduction, dielectric and magnetic propagation losses are calculated for waves guided by parallel plane conductors. The calculations can be applied to other waveguide configurations, such as a microstrip.



For the ferrite magnetically saturated in the x-direction, the permeability tensor becomes

$$\overleftrightarrow{\mu} = \begin{vmatrix} 1 & 0 & 0 \\ 0 & \mu & -j\chi \\ 0 & j\chi & \mu \end{vmatrix}$$

The permeability tensor elements μ and χ are defined in equation (1), since $\mu = \mu_{xx} = \mu_{yy}$ and $\chi = \chi_{xy}$. The lowest order mode is a TE mode with no x or y dependence and the propagation constant, γ, is given by

$$\gamma = \pm\, k \sqrt{\mu_{eff}}$$

$$\text{with } k^2 = \frac{\omega^2}{c^2}\,\epsilon$$

$$\text{and } \mu_{eff} = \frac{\mu^2 - \chi^2}{\mu}$$

Propagation losses arise from (1) imperfect conductors with conductivity σ (2) dielectric loss and (3) magnetic damping. In the calculation below Gaussian units are assumed.

(A) <u>Conduction loss</u>

The attenuation constant per unit length can be determined[23] approximately from

$$\alpha_c = \frac{W_L}{2W_T}$$

where W_T is the average power transmitted by the wave and

and W_L is the average power loss. W_T and W_C can be written in terms of an "effective" impedance, η_{eff},

$$W_L = \frac{b\ R_s\ E_o^2}{\eta_{eff}^2}$$

where b is a dimension perpendicular to the propagation direction, E_o is the rf electric field $R_s = \sqrt{\pi f/\sigma}$ and f is the frequency. Also,

$$W_T = \frac{ab}{2}\frac{E_o^2}{\eta_{eff}}$$

where

$$\eta_{eff} = \sqrt{\frac{\mu_{eff}}{\epsilon}}$$

Thus,

$$\alpha_c = \frac{R_s}{a\ \eta_{eff}}$$

Here, we have chosen ϵ real but later we "relax" this assumption in order to calculate the losses due to a complex dielectric. Assuming η_{eff} constant, α_c increases as the $\sqrt{f}$, since $R_s = \sqrt{\frac{\pi f}{\sigma}}$. For a ferromagnet η_{eff} is not constant and, therefore, α_c is strongly modulated[24] by η_{eff} near FMR (see fig. 6 of ref. 24). In the high frequency limit as $\mu_{eff} \rightarrow 1$ our expression of α_c can be compared with exact solution[25] of α_c in actual stripline guide structures.

B. Attenuation Due to Dielectric and Magnetic Loss

In most cases of interest both the dielectric constant and permeability are complex. This gives rise to propagation loss of the wave in addition to conduction loss. Let us calculate this contribution. For simplicity let's write

$$\epsilon = \epsilon' - j\,\epsilon''$$

$$\mu_{eff} = \mu' - j\,\mu''$$

The complex propagation constant, γ, can be written as follows[23]

$$\gamma = j\frac{2\pi}{\lambda}\,\left(1 - j\frac{\epsilon''}{\epsilon'}\right)\cdot\left(1 - j\frac{\mu''}{\mu'}\right)$$

$$\text{where } \gamma = \alpha + j\beta$$

$$\lambda = \frac{\lambda_o}{\sqrt{\epsilon'\mu'}} = \frac{c}{f\sqrt{\epsilon'\mu'}}$$

$$c = \text{velocity of light}$$

$$\lambda_o \equiv \text{free space wavelength}$$

In most ferrites $\frac{\epsilon''}{\epsilon'} << 1$, but $\frac{\mu''}{\mu'}$ may not necessarily be less than 1.

There are two cases to consider: (1) off resonance and (2) near resonance conditions of the ferrite

1) Off resonance condition

If the internal or the effective magnetic field biasing the ferrite is low compared to the required FMR field, then

$$\mu' \rightarrow 1 - \frac{4\pi M}{\omega/\gamma} \quad C\ ;\ C < 1$$

$$\mu'' \rightarrow \frac{H\Delta H}{(\omega/\gamma)^2}$$

so that $\frac{\mu''}{\mu'} << 1$

After expanding the square root in γ and collecting terms linear in ϵ'' and μ'', we get

$$\lambda\ \alpha \sim \pi \left(\frac{\epsilon''}{\epsilon'} + \frac{\mu''}{\mu'}\right) \equiv (\alpha_D + \alpha_m)\ \lambda \qquad (2)$$

$$\text{or } \alpha \sim \pi f \left(\frac{\epsilon''}{\epsilon'} + \frac{\mu''}{\mu'}\right)/\upsilon\ ;\ \upsilon = \frac{c}{\sqrt{\epsilon'\mu'}}$$

The extra term we have introduced in this calculation is μ''/μ'. The propagation losses are additive with respect to ϵ'' and μ''. Assuming $\frac{\epsilon''}{\epsilon'}$ constant with frequency[26] we see that the dielectric contribution to α increases with frequency (α_D α f). The magnetic contribution decreases with frequency (α_m α 1/f), since $\mu'' \rightarrow 1/f^2$. Thus, the dielectric loss of a ferrite imposes the upper limit in frequency of operation for off-resonance type devices.

2) <u>At resonance condition</u>

For this condition

$$\mu' \sim 1$$

$$\mu'' \sim \frac{4\pi M}{\Delta H}$$

Obviously, the magnetic losses are quite high and dominant factor in a FMR device design. The propagation loss assumes this functional relation

$$\alpha \sim \pi f \left(\frac{\epsilon''}{\epsilon'} + \sqrt{2 \frac{\mu''}{\mu'}} \right) / \upsilon$$

Again the dielectric and magnetic losses are additive.

In summary the limiting factor for very high frequencies of operation is the dielectric loss of the ferrite, since it increases with increasing frequencies. This conclusion applies to off-resonance ferrite devices. As for conductor loss it is possible to devise waveguide schemes[25] which tend to minimize this type of propagation loss. However, it should be pointed out that one may minimize conduction losses at the *expense* of increased radiation losses. This means that as the radiation losses are increased, "cross-talk" between guide systems increases.

IV. CONCLUSIONS

(A) Cubic ferrites are presently used in off-resonance devices operating at x-band and lower frequencies. For frequencies above x-band and possibly near 60 GHz cubic ferrites have been used, but at 90 GHz and above cubic ferrites are inefficient even for off-resonance devices. It is clear that there can be *no* FMR devices which use cubic ferrites at and above x-band.

(B) We expect hexagonal ferrites to be operational up to 500 GHz. However, in order to accurately predict device performances at these frequencies a number of characterization measurements are needed on these materials. Presently, there is little data on $4\pi M$, ΔH, μ and ϵ on hexagonal ferrites. An idealized uniaxial ferrite material for mm wave use should have the following magnetic properties:

$$H_A \geq 30 \text{ kOe}$$

$$4\pi M \sim 5000 \text{ G}$$

$$\Delta H \leq 50 \text{ Oe}$$

$$\Delta H_K \leq 50 \text{ Oe}$$

$$h_c \simeq \frac{1}{4} \text{ Oe (Suhl instability field)}$$

$$H_c \leq 5\text{-}10 \text{ Oe (coercive field)}$$

(C) The limiting factors of hexagonal ferrites at frequencies above 500 GHz may possibly be too high dielectric propagation loss.

(D) Beyond 500 GHz antiferromagnetic materials [27] may have to be explored for possible use in mm wave devices.

(E) Finally, it is clear that in order to make the mm wave technology feasible and competitive, cheap (~ 100 $) component devices must be developed. This has not been accomplished so far. Planar microwave integrated

circuits offer this possibility, either for semiconductor or ferrite materials.

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